EVALUATION OF THE MONITORED DATA FROM A GRID-CONNECTED PHOTOVOLTAIC SYSTEM AT NUNAVUT ARCTIC COLLEGE, IQALUIT, NWT (CANADA)

Didier Theve...
Numerical Logics Inc.
119 University Avenue East
Waterloo, Ont.
Canada N2J 2W1
numlog@sympatico.ca

Lisa Dignard, Sylvain Martel, Michael Ross, Dave Turcotte
NRCan/CANMET
Energy Diversification Research Lab
1615 Boulevard Lionel-Boulet
Varennes, Que. Canada J3X 1S6

Sharon Troke
Nunavut Research Institute
Box 1720
Iqaluit, NWT
Canada X0A 0H0

ABSTRACT

In July of 1995, a 3.2 kWp photovoltaic system was installed on the southern facade of the Nunavut Arctic College in Iqaluit, NWT, near the Arctic circle. The project had two principal objectives: first, to publicize photovoltaics as a viable power source in the eastern Arctic, and second, to document the long-term performance of a grid-tied photovoltaic system in the Northwest Territories.

This paper presents a comprehensive evaluation of the performance of the system in its first two years of operation. Climatic and solar radiation conditions at the site are reviewed, and the performance of all the components of the system (PV array, maximum power point tracker, inverter) is analyzed. Energy delivered to the grid and overall system efficiency are also analyzed on a monthly and hourly basis.

Hourly simulations with WATSUN-PV, a photovoltaic system simulation software developed by the University of Waterloo, are done to analyze PV module temperature and to compare actual with theoretical system performance. Discrepancies between simulation and monitored data are evaluated.

1 - INTRODUCTION

1.1 - Background

It is projected that grid-tied photovoltaic systems will become cost-effective in northern Canada before they do so in southern Canada. No community in the Northwest Territories is connected to the North American electrical grid. Rather, each community, or cluster of communities, has a local grid. The majority of these local grids rely on diesel gensets for their electricity; the diesel fuel can be extremely expensive in the Northwest Territories due to the high cost of transportation. As a result, the true cost of electricity is very high. Even though the photovoltaic system will generate very little power during the winter, the reduction in fuel use during the summer can make the photovoltaic system attractive. Assuming moderate annual reductions in the cost of photovoltaic technology, such grid-tied photovoltaic systems will be cost-effective in about 15 years to 25 years.

One barrier to the implementation of major grid-tied photovoltaic systems in Northern communities may be skepticism of the technology's ability to function in the North. Furthermore, when evaluating the economics of the system, hard data from an actual Northern installation will be more convincing than simulations alone or data based on southern installations. For these reasons, it was decided in 1995 to install a photovoltaic system on the facade of Nunavut Arctic College in Iqaluit, N.W.T. The Iqaluit

system is meant to provide hard data about grid-connected photovoltaic systems in Canada's north, as well as publicize photovoltaics as an alternative source of power in the Arctic.

1.2 - System Overview

The system installed at Nunavut Arctic College is shown in Figure 1. There are 60 PV modules arranged in 5 parallel groups of 12 modules in series. Three of the groups are composed of 36 Siemens M55 modules and the remaining two groups are composed of 24 Solec S-53 modules. Total module area is 25.62 m^2. The modules are placed vertically on the front facade of the college, which faces 30 ° West of South. The array output at nominal conditions (insolation 1000 W/m^2, PV array temperature 25 C) is 207± 2V, 15.25 A DC for a total output of 3.18 kW DC. The nominal array efficiency is 12.4 %.

The PV array is connected to a Prosine 5000 GT 3-kW power conditioner built by Statpower Technologies of Burnaby, B.C. Its nominal output is 208 V. It is connected to two phases of the 3-phase 120 V electrical AC system of the building.

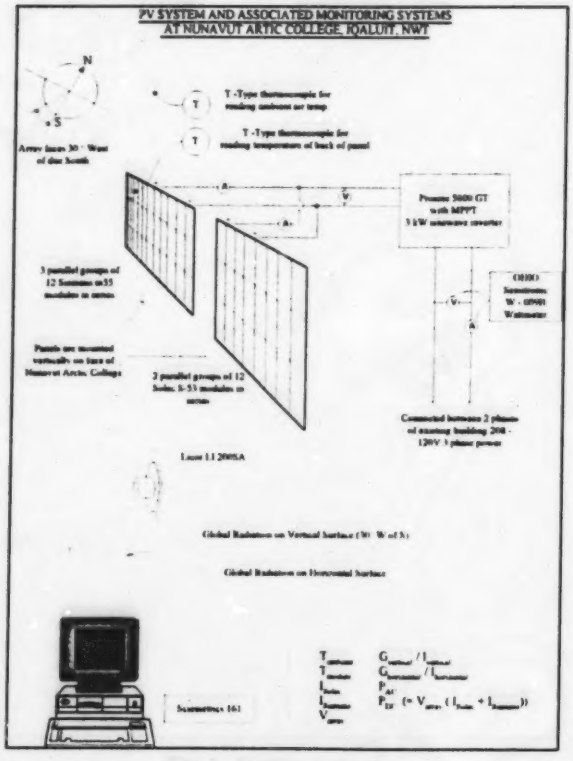
PV SYSTEM AND ASSOCIATED MONITORING SYSTEMS
AT NUNAVUT ARTIC COLLEGE, IQALUIT, NWT
N
S
T -Type thermocouple for reading ambient air temp
T -Type thermocouple for reading temperature of back of panel
Array faces 30 ° West of due South
Prosine 5000 GT with MPPT 3 kW inverter/converter
3 parallel groups of 12 Siemens m55 modules in series
2 parallel groups of 12 Solec S-53 modules in series
Panels are mounted vertically on face of Nunavut Arctic College
Connected between 2 phases of incoming building 208 - 120V 3 phase power
Global Radiation on Vertical Surface (30° W of S)
Global Radiation on Horizontal Surface

Fig. 1 - System overview.

The system has been monitored continuously since its installation. Every minute and a half, a datalogger records insolation on a horizontal surface and in the plane of the PV array, ambient temperature, array temperature, PV array current and voltage, DC power generated, and AC power delivered to the grid. Data is averaged every hour before being stored to disk on a computer.

2 - SYSTEM PERFORMANCE

Horizontal and vertical solar radiation were correctly monitored since July 1995. AC power appears to have been monitored properly since mid-August 1995. The rest of the data were properly monitored only after March 1996. After that date, and with the exception of the system clock and of possibly one or two sensors, the monitoring system appears to have worked properly and provided extremely valuable information about the photovoltaic system.

2.1 - Weather data

Horizontal and vertical solar radiation is measured with Li-Cor pyranometers. Monthly mean daily horizontal radiation was found to lie most of the time within one standard deviation of the values published by Environment Canada in the Canadian Climate Normals [1]. Similarly, ambient temperature values compare favorably with those published, although they are usually higher by an average of 3 C.

Vertical irradiance also appears to have been recorded properly. Monthly mean daily radiation in the plane of the PV array was compared with values predicted from monthly mean daily horizontal radiation by the Solar Resource module of RETScreen™ [2]; the two were found to be within 7 % of each other over the July 95 - September 97 period, which is very satisfactory. On an annual basis, the recorded amount of solar energy falling on the PV array during that period oscillated between 25.3 and 26.8 MWh/year. Because of the high latitude of the site, there is of course a very strong seasonal dependency of available solar radiation in the plane of the array. Seasonal variations of vertical irradiance and temperature are illustrated on Figure 2.

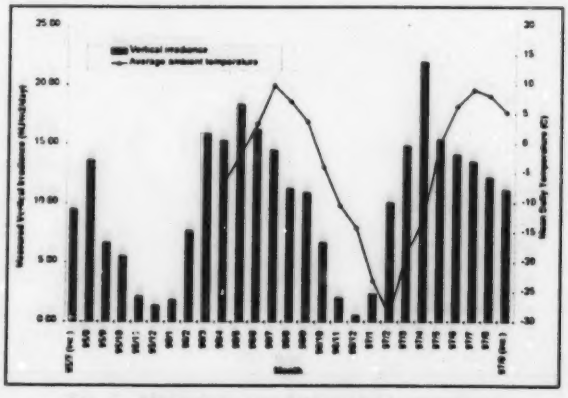

Fig. 2 - Mean daily irradiance and temperature.

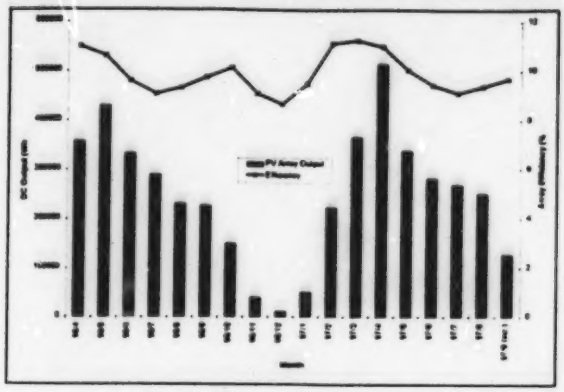

Fig. 3 - PV array performance.

2.2 - Photovoltaic Array

The performance of the photovoltaic array is analyzed in Figure 3, for the period April 96 - September 97. On a monthly basis, the array DC output varied from 0.011 MWh in December 96 to 0.513 MWh in April 1997. The monthly average efficiency, defined as DC output produced divided by incident radiation, averaged 9.9 % during the same period. The efficiency was between 11.0 and 11.2 % in February, March and April, when the array worked under abundant sunlight and in low ambient temperature. Efficiency was lower in November, December and January (down to 8.6 %) because of low sunlight conditions. Between June and September, when it operated at higher temperatures, the array efficiency was between 9.0 and 9.7%.

2.3 - Power Conditioning Unit (PCU)

The power conditioning unit (PCU) transforms the DC current from the PV array into AC current that is fed to the grid. It comprises an inverter and a maximum power point tracker.

The PCU appears to have turned on whenever sunshine was available. Figure 4 shows the hourly efficiency of the power conditioner as a function of the DC power input for the whole monitoring period. The curve is smooth and shows that the power conditioner behaves predictably. The maximum observed efficiency of this 3 kW PCU is around 90%. This is slightly lower than the 94 % maximum efficiency observed during testing of the Prosine GT in a 5 kW configuration at CEDRL. The different inverter configuration may explain the discrepancy between the two values. As expected, the efficiency decreases at low power. This is due to 1) the electronics, which are fine-tuned for an optimal operating point, and do not perform as well at low power and 2) there is a basic amount of power required to operate the unit irrespective of the output power.

Measurements demonstrated that the PCU starts drawing power from the grid when the PV array power falls below 100 W. Laboratory tests show that the power drawn from the grid then reaches a maximum of around 35 W when no power is available from the PV array. Subsequently, the PCU turns off at nighttime and the power consumption falls below 2 W. For a typical day, the PCU would wake-up at dawn and start consuming 35 W of power from the grid. As the output of the modules increases, consumption of grid power decreases until 100 W is available from the PV array. During winter months in the far North, the PCU may operate a long period of time with less than 100 W available from the PV array, thus consuming power and reducing its overall efficiency. This explains the significant dip in efficiency observed in Figure 5 for the month of December.

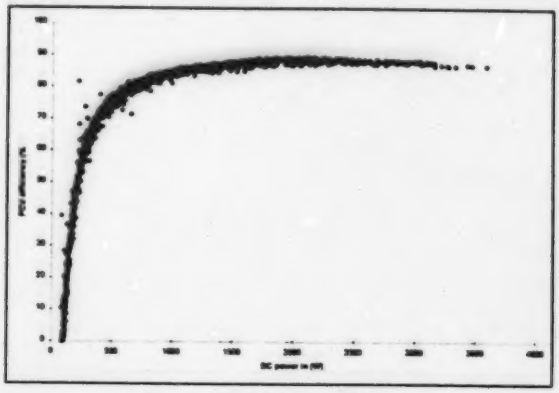

Fig. 4 - PCU hourly efficiency.

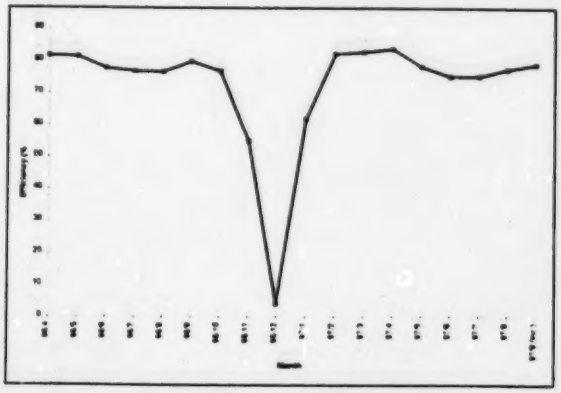

Fig. 5 - PCU monthly efficiency.

For the rest of the year, the efficiency varies between 75.2 % and 83.6 %, with a seasonal trend: efficiencies are higher from February to April (between 81.6 % and 83.6 %) than between June and September (between 75.2 % and 79.7 %). This seasonal trend is mainly due to the efficiency curve of the PCU (Figure 4). Summer days are longer than spring and fall days but they are characterized, especially in the far North, by a long low-light period. Figure 5 shows that this has a negative effect on the summer PCU efficiency since the power

conditioner is operating at low power for a larger fraction of the day.

2.4 - Whole system

Monthly system output and efficiencies are shown in Figure 6. The system delivers between 0.4 kWh (December 1996) and 429.2 kWh (April 1997) per month. Total output is 1,982.3 kWh for the period September 1995 - August 1996, and 2,131.2 kWh for the period September 1996 - August 1997. Monthly system efficiency follows closely the monthly efficiency curves of the PV array and the power conditioner; efficiency is around 9 % from February to April, and between 7 and 8 % from May to September. The curve dips from November to January because the power conditioner works less efficiently at low DC power and the PV array efficiency is lower during low light conditions.

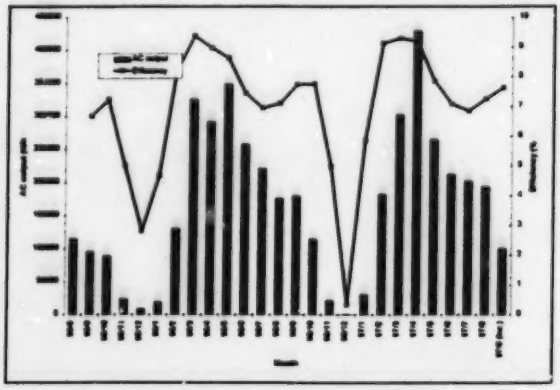

Fig. 6 - Monthly system output and efficiency.

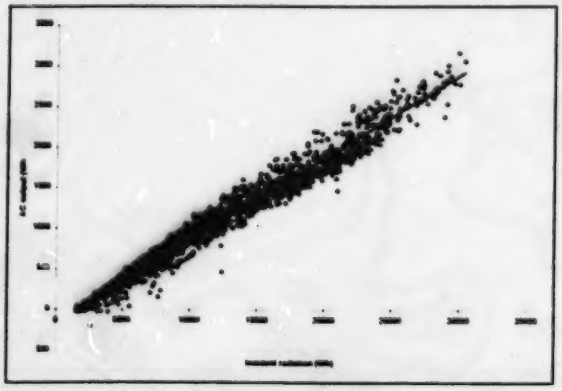

Fig. 7 - Hourly system output

Figure 7 shows the hourly system efficiency for the whole monitoring period, for irradiance levels greater than 60 W/m^2. It should be noted that the system output is close to linear ($R^2 > 0.98$) and can be approximated by the following relationship:

$$\text{AC output} = 0.1 \times \text{Incident radiation} - 150$$

where both AC output and incident radiation are expressed in Wh.

3 - SIMULATIONS

Simulations of the Iqaluit system were performed with the WATSUN-PV photovoltaic systems simulation software [3]. The purpose of the simulation was twofold:

- provide additional analysis of the system by comparing experimental data with that of an 'ideal' system;
- validate the WATSUN-PV software for use in Canada's north, and point to areas of improvements in the simulation algorithms used.

For an overview of the WATSUN-PV program, the reader is invited to refer to [5] which presents a description of the various models used in the program.

Two simulations are presented in this paper. The first simulation used monitored vertical irradiance values and the actual PCU efficiency curve from Figure 4. This setup models the system as it is, minimizes potential errors in the calculation of irradiance in the plane of the PV array, and provides direct comparison of predicted array efficiency, array temperature, and system output, with monitored values. A second simulation used horizontal rather than vertical irradiance, in order to show the precision of the tilting algorithms used in WATSUN-PV at high latitudes.

3.1 - Simulation setup

WATSUN-PV is not capable of simulating a parallel connection of two sub-arrays with different module characteristics. As a result, simulations were run with parameters for the Siemens modules only. The reasoning behind that choice is that there are more Siemens modules than Solec modules in the system, so they are likely to have a preponderant influence in terms of maximum power point and operating voltage. It should be noted, however, that the power conditioning unit will try to maximize the total output of the PV arrays, and therefore choose an operating voltage which will likely not correspond to the maximum power point of either sub-array.

Simulation parameters came from specification sheets provided by the manufacturers. Monitored insolation and ambient temperature data were used. It should be noted that the time base used by WATSUN-PV, local apparent time, differs from the time base used for the monitoring, local standard time. Because of the large errors in the times recorded in the experiment, no attempt was made to convert from one time base to the other. Weather data were simply translated to the closest whole hour. This left a few gaps in the data, for which monitored variables were

considered to be zero. Wind velocity near the PV array is not monitored. Instead, monthly average wind velocities derived from the Iqaluit TMY file [4] were used. The values were held constant during each month. Albedo was assumed to be 0.7 when the average daily temperature fell below -5 C, and 0.2 when the average daily temperature was greater than 0 C. A linear interpolation was performed between these two thresholds.

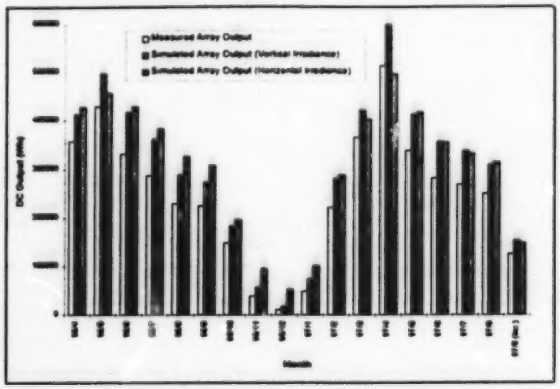

Fig. 8 - Measured and predicted array output.

3.2 - Simulation #1 with monitored vertical irradiance

3.2.1- PV array

Figure 8 compares measured and predicted array output, on a monthly basis. Over the simulation period, WATSUN-PV predicts an array output of 5.458 MWh, vs. 4.472 observed experimentally, i.e. an overestimation by 22.0 %.

The difference between simulation and experimental results may be attributed to three factors. The first one is that WATSUN-PV models the array as if made of Siemens modules only; it does not take into account the slight mismatch between Siemens and Solec modules, which will make each sub-array work somewhat off its maximum power point. Even if only Siemens modules were used, there would be slight variations in the characteristics of each module, and the whole array would likely be less efficient than each module taken individually. The second factor is that WATSUN-PV models an 'ideal' array, made of clean modules. In practice, dust may accumulate on the arrays, making them slightly less efficient. Finally the third factor is that at low radiation levels the modules are less efficient than predicted by models.

Figure 9 shows PV array temperature predicted by WATSUN-PV, vs. measured values. There is, generally speaking, a reasonable agreement between simulated and experimental values. The mean bias error (MBE), calculated for hours where vertical solar irradiance is greater than 5 Wh/m^2, is -1.25 C, and the RMSE is 3.60 C.

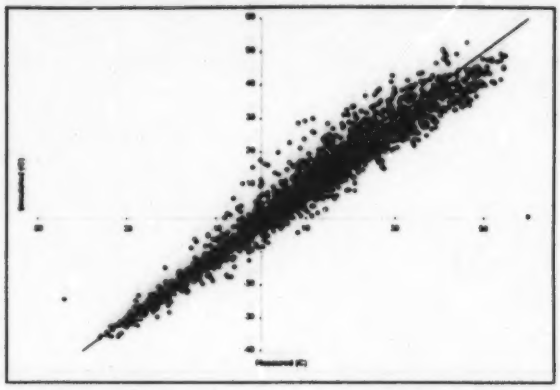

Fig. 9 - Simulated vs. measured array temperature.

3.2.2 - Whole system

Figure 10 shows the measured and simulated system output, on a monthly basis. Over the whole simulation period, predicted energy production is 4.408 MWh vs. 3.525 MWh actually measured, an over-prediction of 25.0 %. In relative terms, the difference is greater during the winter months than during the summer months.

The ability of the WATSUN-PV program to predict AC output for this northern system seems slightly lower than that for southern systems [5], where the overestimation of system performance by the program was between 5 and 10 %.

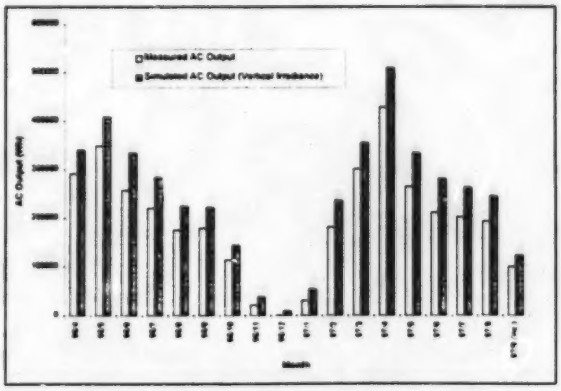

Fig. 10 - Measured and simulated system output.

3.3 - Simulation #2 with measured horizontal irradiance

A simulation run with horizontal irradiance data (using WATSUN-PV's Hay algorithm to compute vertical irradiance from horizontal irradiance) is shown together with measured array output and simulation #1 (using vertical irradiance and therefore bypassing WATSUN-PV's tilt algorithm) on Figure 8. Array output using horizontal irradiance data is constantly and substantially

higher than the one obtained using vertical irradiance data from August 1996 to January 1997. In May 1996 and April 1997, the use of horizontal irradiance leads to lower values of array output. For the other months, i.e. April, June and July 1996, February and March 1997, and from May to September 1997, the results with horizontal irradiance and vertical irradiance are very close.

For the winter months (November 1996 to January 1997) it is understandable that the tilting algorithm used in WATSUN-PV does not perform well, because the sun is very low on the horizon. The rest of the time it is not clear why the tilting algorithm seems to perform better for some months than for others. Particularly, the algorithms seems to give accurate values in the summer of 97 (July to September) whereas it over-predicts for the same period in 96. However these results are to be used with extreme caution, since the time recorded by the experiment is not known with sufficient precision. A shift of one or two hours may well have happened at some time during the course of the experiment. This would jeopardize the calculation of vertical irradiance from horizontal irradiance, which makes use of the zenith and azimuth angles of the sun.

Over the whole simulation period, system output predicted by WATSUN-PV using horizontal irradiance amounts to 4.524 MWh, vs. 4.408 MWh using vertical irradiance and 3.525 MWh monitored.

4 - CONCLUSIONS

The PV system appears to have worked reliably and well during its two years of operation, generating a total output of 1.98 MWh for the period September 1995 - August 1996, and 2.13 MWh for the period September 1996 - August 1997. Array efficiency is around 11.2 % when the array operates under optimal conditions, and can be as low as 8.6 % during the winter months. The power conditioning unit (PCU) appears to have worked at a lower efficiency (90 % max.) than anticipated. The reason why this happened is unknown. It is estimated that this penalized the overall performance of the system by 7%.

Simulations with WATSUN-PV, using irradiance measured in the plane of the PV array, monitored ambient temperature, and monitored PCU efficiency, lead to energy predictions 25.0 % higher than measured. The differences can be attributed to the fact that WATSUN-PV models 'ideal' modules, and that it tends to over-predict the performance of modules under low sunlight conditions.

Using monitored horizontal irradiance data leads to a greater over-prediction by the program. This over-prediction is caused by the tilting algorithm that converts horizontal irradiance to irradiance in the plane of the PV array.

Overall, the performance of WATSUN-PV for the simulation of the Iqaluit system appears satisfactory. Although, improvements in the PV array model to make it more accurate at low sunlight conditions and to make the tilting algorithm more accurate for high latitudes, would increase the precision of the program when used for the simulation of Northern systems.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Stuart Doherty for assistance in analyzing the data and setting up the simulations, as well as Mr. Mathieu Chevrier for the improvements he made to the monitoring equipment and for the careful calibration work he performed at the Nunavut Arctic College site.

REFERENCES

1. Environment Canada, Atmospheric Environment Service, *Canadian Climate Normals 1951-1980. Volume 1, Solar Radiation; Volume 2, Temperature*. Canadian Climate Program (1982).

2. Natural Resources Canada / CANMET, Energy Diversification Research Laboratory. *RETScreen™ - Renewable Energy Technologies Project Assessment Tool - Beta Version*. Report # EDRL 97-59 (TR). CANMET Energy Diversification Research Laboratory, Natural Resources Canada, P.O. Box 4800, Varennes, Que., Canada J3X 1S6.

3. Watsun Simulation Laboratory, *Watsun-PV 6.0 - User's manual and program documentation*. Watsun Simulation Laboratory, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1.

4. Watsun Simulation Laboratory, *Typical Meteorological Year (TMY) Weather Files*. Watsun Simulation Laboratory, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1.

5. Thevenard, M. Zagorsek, M. Chandrashekar, *Computer Modeling of a Photovoltaic Grid-Connected System*, Proc. 20th Annual Conference of the Solar Energy Society of Canada (SESCI), October 30 - November 2, 1994, Ottawa, Ont., Canada, pp. 51-55.